AFRL/NASA Flywheel Program Overview

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OUTLINE

- Introduction
- Flywheel Program Challenges
- Flywheel Applications
- AFRL/NASA Programs
- What’s next for Flywheels
- Conclusions

Introduction

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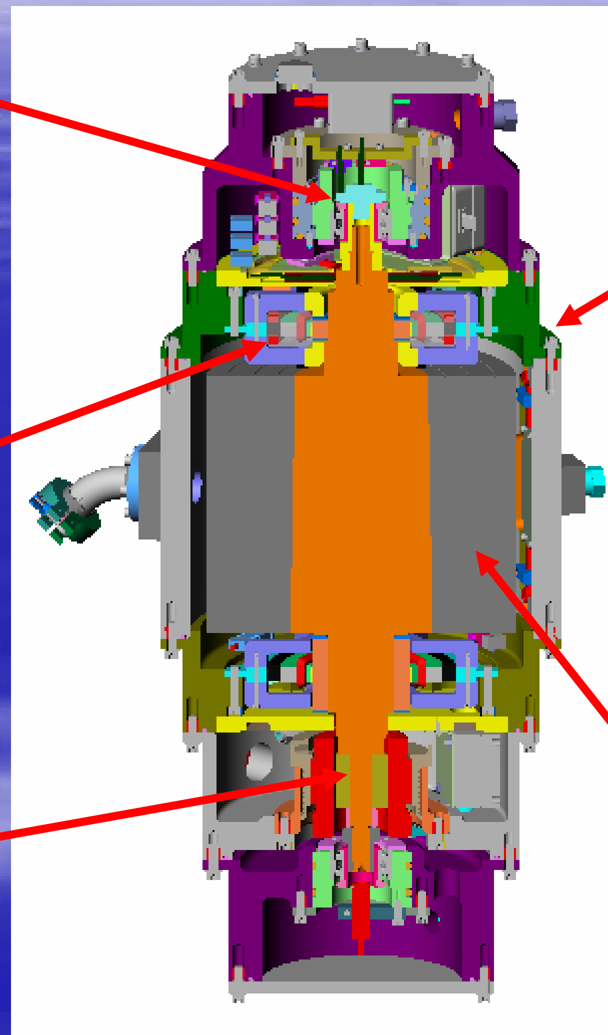
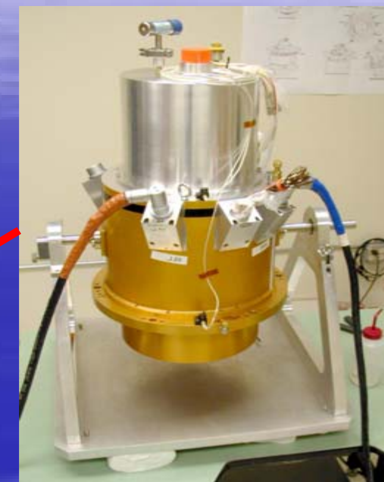
What is a Flywheel?

Auxiliary Bearings

Magnetic Bearings

Motor/Generator/Electronics





Housing

Rotor

Flywheel Energy Systems

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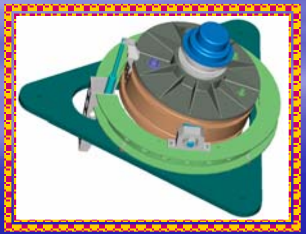
Flywheel Energy Storage (FES)


- 2 counter-rotated flywheels
- Energy storage
- Replace some Power Management & Distribution (PMAD)

Integrated Power & Attitude Control System (IPACS)

- Array of $\geq$ 2 FWs
- Energy storage & Attitude control torque
- Replace some PMAD



Flywheel Attitude Control, Energy Transmission & Storage (FACETS)

- System Level – Full 3-axis Attitude Control with Simultaneous Energy Storage

Flywheel Program Challenges

Technical Challenges

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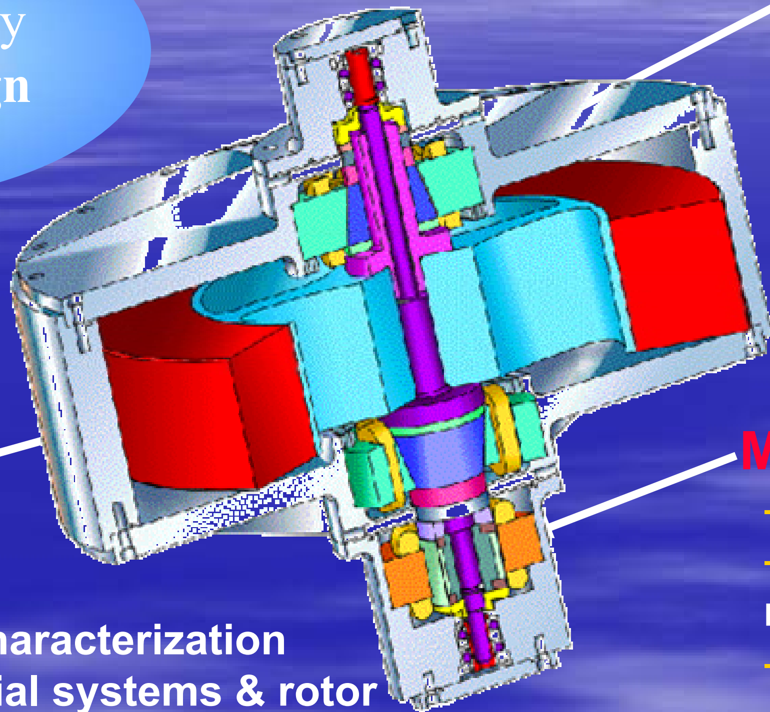
Flywheel systems represent a highly **integrated design** challenge



Magnetic Bearings:
- **Base motion: gimbaling**
- **Disturbance rejection**
- **Low Losses: actuators, sensors, controls**

Motor/Generator:
- **Low losses**
- **Drive control for low torque ripple**
- **Efficient power converter**

Rotor:
- **SAFETY**
- **Rotor Safe Life characterization**
- **Composite material systems & rotor structures for high specific energy**
- **Health monitoring/ fault recovery**

System Level:
- **Simultaneous energy storage & attitude control with fixed wheels**
- **System level efficiency**
- **CMG mode attitude control with variable speed momentum wheels**

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Programmatic Challenges

- Development
  - Bus technology: Low priority
  - Simultaneous AC & ES control: To decouple or not to decouple?
- Demonstration
  - Modeling and simulation: Simultaneous control
  - Facilities: Adequate to measure key parameters
  - Safety: "You are going to spin this how fast?!"
- Transition
  - Revolutionary : "we've never flown one before"
  - Pervasive: Challenge to user confidence
  - The time is NOW! Technology has been funded long enough?
  - Find the HIGH Payoff Application! ES or IPACS?

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Flywheel Applications

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Flywheel Benefits

- High System Specific Energy
- High Specific Power
- Long Life
- High Round Trip Efficiency
- Multiple Functionality (Power and Torque)
- Design and Operational Flexibility
- Long Storage Life Without Degradation

The Ultimate Spacecraft Battery

Potential Flywheel Applications and Products

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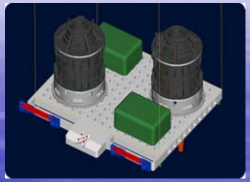
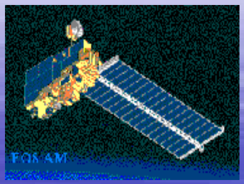
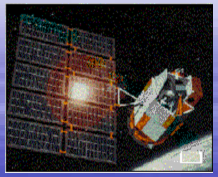
Yellow = IPAC
Green =Energy Storage
Red = Power Peaking, Pulse Power



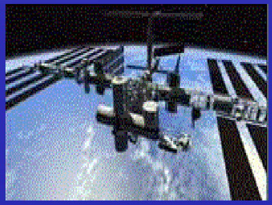
Flywheel Express Pallet Experiment
(NASA, AF, Commercial)



Integrated Power/Attitude Control
(NASA, AF, Commercial)



Constellations / Micro-Sats
(NASA, AF, Commercial)



ISS (NASA)

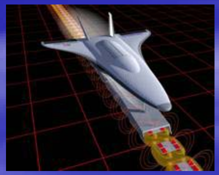
UPS (NASA, Industry)

Utility Peaking
(NASA Lunar/Mars)

Tether
Reboost

Aircraft/RLV
(Military, Commercial, NASA)

Vehicles (NASA Rover, Military Combat)



Mag Lev Launch
(NASA)

Near Term

WHEN

Far Term

AFRL/NASA Programs

AF/NASA Technical Approach

- Develop advanced aerospace flywheel component and system technologies to meet AF & NASA long term mission needs
  - Energy Storage
  - Integrated Power and Attitude Control
  - Power Peaking & Pulse Power
- Near term technology focus on
  - "Millennium" class, >1kW-h, for large satellites
  - "Century" class flywheels, 300-700 W-h capacity, for mid-sized satellites
- Longer term development of flywheels, < 300WHr capacity, for small satellite applications
  - Address scaling effects to achieve performance goals

AF/NASA Technical Approach

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- Demonstrate flywheel technology goals
  - System Specific Energy (usable) > 50 W-h/Kg (within 5 years), > 200 W-h/Kg long term
  - Conventional Momentum Storage capability at Min. speed (>2x at Max. speed)
  - Cycle Life > 75,000
  - Round Trip efficiency > 90%
  - System Cost Reductions > 25%

National Aerospace Flywheel Program Players

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Government Agencies

AFRL | NASA | DARPA
Army | Navy | Aerospace Corp
NRO | DOT | NCC

Aerospace Primes

Lockheed Martin | NGST | Boeing
Honeywell | Loral

Small Business

Applied Mat'l Tech., Inc | Ashman Tech. | OES | FESI
Foster Miller | Test Devices | AFS Trinity | Think Composites
Mohawk Innovative Tech., Inc | TBC | Calnetixs

Universities

AF Academy | Univ. of Wisconsin | Univ MD | Univ of Toledo
Air Force Institute of Tech | Univ VA | Univ TX CEM | Auburn
VA Tech | TX A&M | Penn St

System Development

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NASA Flywheel Technology Development Approach

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System Application Challenges

- Power/Momentum Mgmt.
- High Specific Energy
- Efficiency
- Safety
- High Specific Power
- Deployment
- System Integration

Component Technology Development Challenges

- Rotors
- Magnetic Bearings
- Motor/Power Electronics
- Systems/Controls

Integrated System Demonstrations

- Power Momentum Mgmt.
- Energy Density
- Efficiency

Flight Systems

NASA Systems Technology

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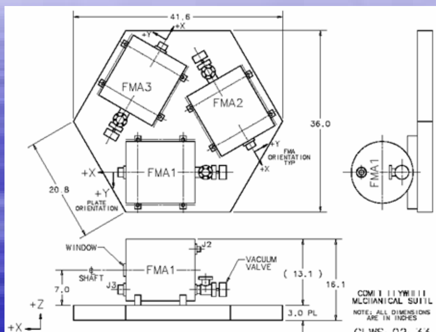

COMET Layout

GRC Air-table
2 module test

Objectives

- *Develop multi-wheel systems and demonstrate ability to cycle while controlling torque.*
- *Define impacts of flywheel disturbances on attitude control.*
- *Address failure modes on both attitude control and power systems at spacecraft level.*

Approach

- *Conduct 2 module (single axis) air table testing using GRC hardware (on magnetic bearings)*
- *Conduct 3 module (2 axis) force table testing with Lockheed (COMET) hardware (on mechanical bearings)*

Technology Status

- *GRC single axis torque control approach (air-table fixed and free) demonstrated in April tests*
- *Conduct full scale power and torque tests on air-table in FY04*
- *GRC/Lockheed Martin COMET dual axis torque demonstration in April 2004.*

Single Axis Integrated Momentum and Power Control with Flywheels

D1

High Speed Shaft

G2 Development Objectives

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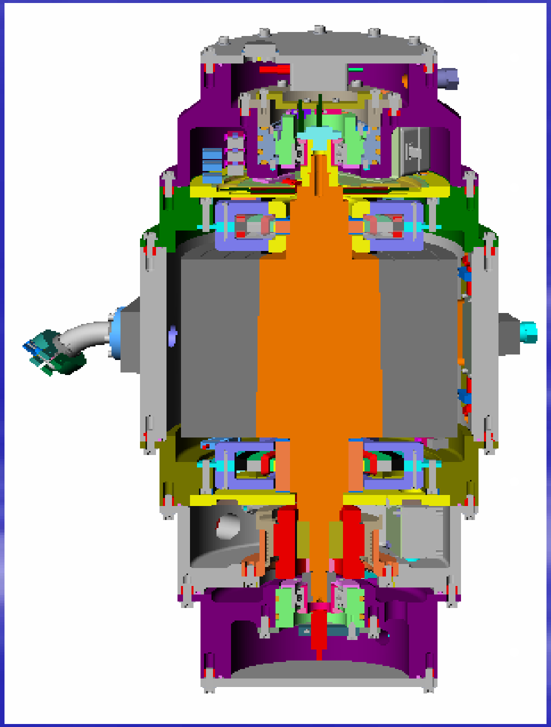
Mid-sized Demonstrator for Component Technology

G2 will be used to demonstrate emerging component technology at a flywheel module level of integration. Candidates include:

- Composite arbors
- Advanced rim systems
- Redundant, high efficiency magnetic bearings
- High efficiency motor/generators
- Advanced touchdown bearings.

Layered design allows insertion of new components without major flywheel module redesign

- All power, signal, and thermal connections are made at the layer that uses them
- Layers use standard mating and sealing interfaces to maintain vacuum enclosure



System Technology Building Block

Full scale power and momentum capabilities can be demonstrated

G2 and existing D1 modules will be used in FY04 to conduct full scale performance testing on air-table

G2 is an option for future full scale performance demonstrations of the COMET type system on magnetic bearings

Taking the Next Steps

Four G2 modules can be used in a ground demonstration of three axis attitude control and bus regulation on magnetic bearings

Experience gained on G2 will be used to develop an advanced technology prototype that meets near term performance goals and metrics

FESS Program Status

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- Completed CDR – 9/11/01.
- Hardware fabrication started – 11/01.
- Hardware fabrication status:
  - All component fabrication completed except T1000 outer bands, magnetic bearings, and EM electronics – 11/02.
- Rotor certification status:
  - Safety approach developed in conjunction with JSC – 9/01.
- FESS is a flight prototype design and is a top candidate for first flight

FESS Components

Motor/Generator Components and Tooling

Rotor Components and Tooling

AF System Level Development

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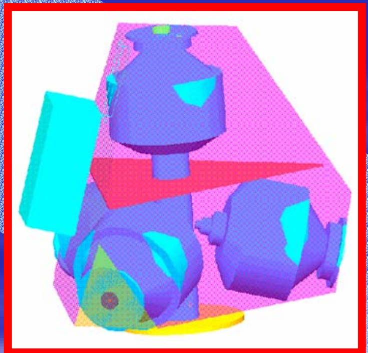
Integrated Power and Attitude Control System (IPACS) Development

- IPACS testing (Honeywell)
- Flywheel Rotor Safe-Life Program (NASA/Aerospace)
- Magnetic bearing control research (Ga Tech/Va Tech)
- Rotor dynamics (Auburn)

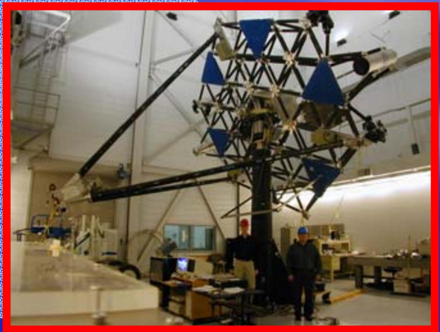
- Simultaneous attitude and charge/discharge control
- Solid modeling of IPACS (Honeywell)
- System level simulation



Flywheel Attitude Control, Energy Transmission & Storage (FACETS) Development

Agile Multi-Purpose Satellite Simulator (AMPSS) Integrated Demonstration

- FEM/Solid modeling of structural test-bed (Boeing SVS/CSA)
- System level mathematical and HWIL simulation (Boeing SVS)
- FACETS HW integration



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Government Facilities

NASA Flywheel Technology Program
High Energy Flywheel Facility (HEFF)

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Objectives: Develop facility to conduct flywheel system development for integrated power and attitude control satellite applications

Accomplishments (July 2003)
- Low cost water containment system for safety
- Low-friction air-table operational
- Facility power, control and instrumentation operational
- Safety permit obtained and facility operational (Bldg 333)
- Testing of counter-rotating flywheels, FY02 and FY03

Capability
- Test two or more flywheel modules, up to 700 W-Hr
- 130V DC Bus
- 1200 LBS Capacity
- Digital, automated controls for m/g and mag bearings

Augmentations
- Force Table facility being installed next to HEFF for Lockheed Martin COMET testing in FY04

HEFF Air-Table and Water Containment

HEFF Control Room

AFRL Agile Multi-Purpose Satellite Simulator (AMPSS)

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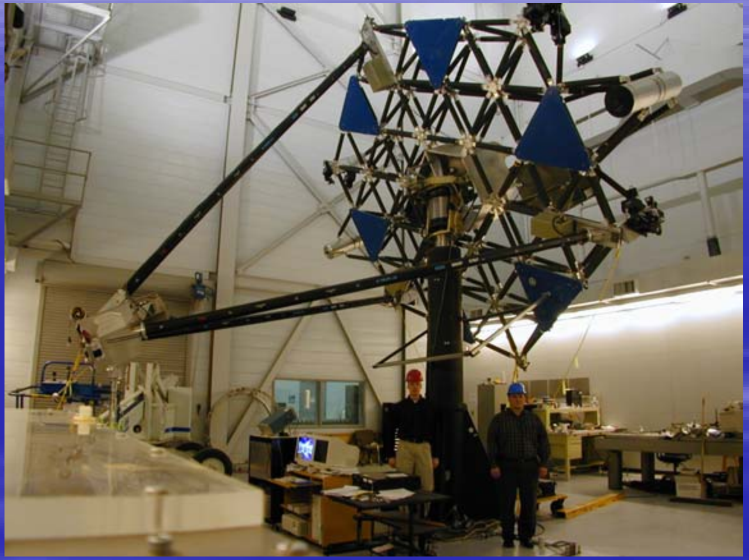
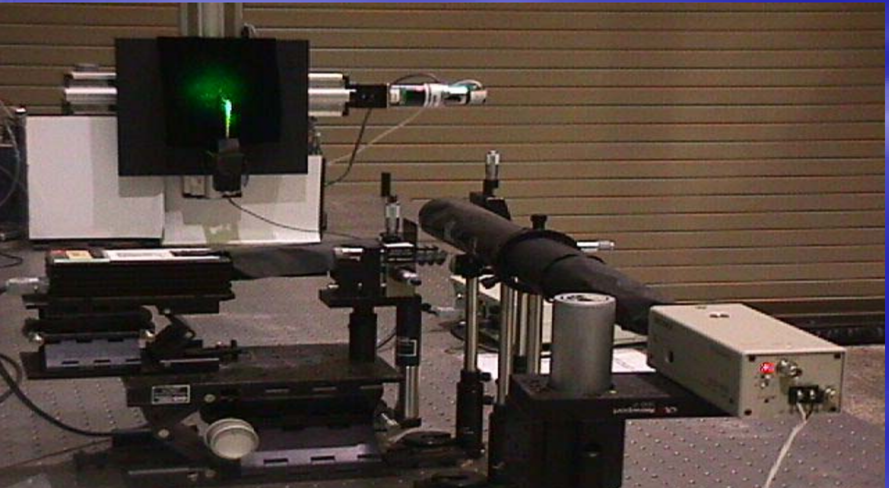
ASTREX

- Structure: 1/3 - 1/2 scale beam expander based on SBL concept (graphite/epoxy)
- Spherical Air Bearing
  - Load capacity: 14,500 lb (air pressure dependent)
  - ±20° Pitch and Roll, ±180° Yaw
- "Smart Structure" with embedded piezo-ceramic sensors/actuators for structural vibration control





Optical ATP

- Optics: Table-top demonstration
- To be tested in coordination with attitude control (flywheels / cmgs) on ASTREX for ATP function

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Base R&T

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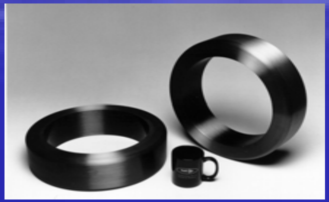
Base R&T - Rotor

Multi-directional Composite Rotor Development
(Auburn Univ., CCDS Cooperative Agreement – NASA)



Optimal Rotor Design/Manufacturing
Optimal distribution of material properties
(Think Composites, SBIR/in-house – AFRL)

Integrated Composite Arbor and Flywheel Rim Technology Development
Development, proof and cyclic tests of high tip speed rotors (Univ. of Texas, Center for Electromechanics, NRA – NASA)

Characterization & Control of Internal Material Damping in Composite Rotors
(Auburn Univ., NRC Summer Faculty Fellowship – AFRL)

Flywheel Rotor Safety/Longevity Program

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- Flywheel Rotor Safety/Longevity Working Group
  - Co-Sponsored by NASA and AFRL and chaired by Aerospace Corporation, Mr. Jim Chang
  - Six Working Group meetings have been held (last one June 03)
  - Rotor Certification Standard in AIAA balloting cycle
- Rotor Cyclic Fatigue Testing
  - FESS Control Rotor testing on hold until FY04
  - Cycling of FESI IPACS/FACETS rotor continues

Base R&T - Bearings

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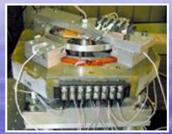
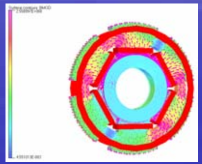
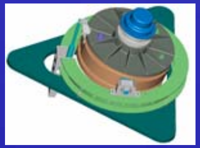


Low/Zero Bias Magnetic Bearing Control
Applied Advanced Nonlinear Control (Georgia Tech, AFOSR – AFRL)

Low-loss, fail-safe magnetic suspension for flywheels
Fault-tolerant bearings; hybrid controls; bearing design tool; expert system for health monitoring (Texas A&M, NRA – NASA)





Magnetic Bearing Control in the Presence of Base Motion
(Virginia Tech, AFOSR – AFRL)

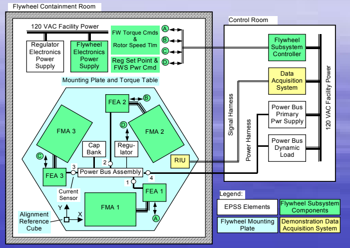
Advanced Flywheel Materials Development for High Specific Energy
Develop high-strength materials for flywheel magnetics (UT-CEM, NRA – NASA)

Flywheel Energy Storage Systems for Small and Medium Spacecraft
Develop high-speed passive radial bearing system (Foster-Miller, Phase II SBIR – NASA)

Novel Damping Concepts for Mechanical Backup Bearings and Passive Magnetically Suspended Rotors (Univ. of Toledo, NRA – NASA)

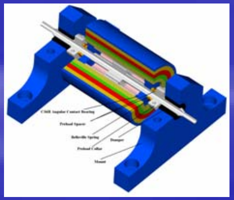
Computational Tracking of Dynamic States / Disturbances in Rotating Machinery
Observer-based magnetic bearing control using extended Kalman filter approach (NASA)

Base R&T - System

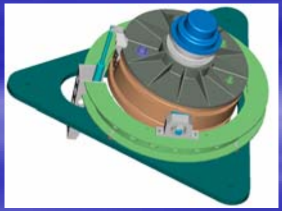


Coordinate Momentum and Energy Transfer (COMET™)
3-DOF System Demonstration in NASA HEFF
(LMCO-CPC, NRA – NASA)

Simultaneous Energy Storage & Attitude Control
Collaborative control algorithm development
(Air Force Academy, Ga Tech EPA – AFRL)



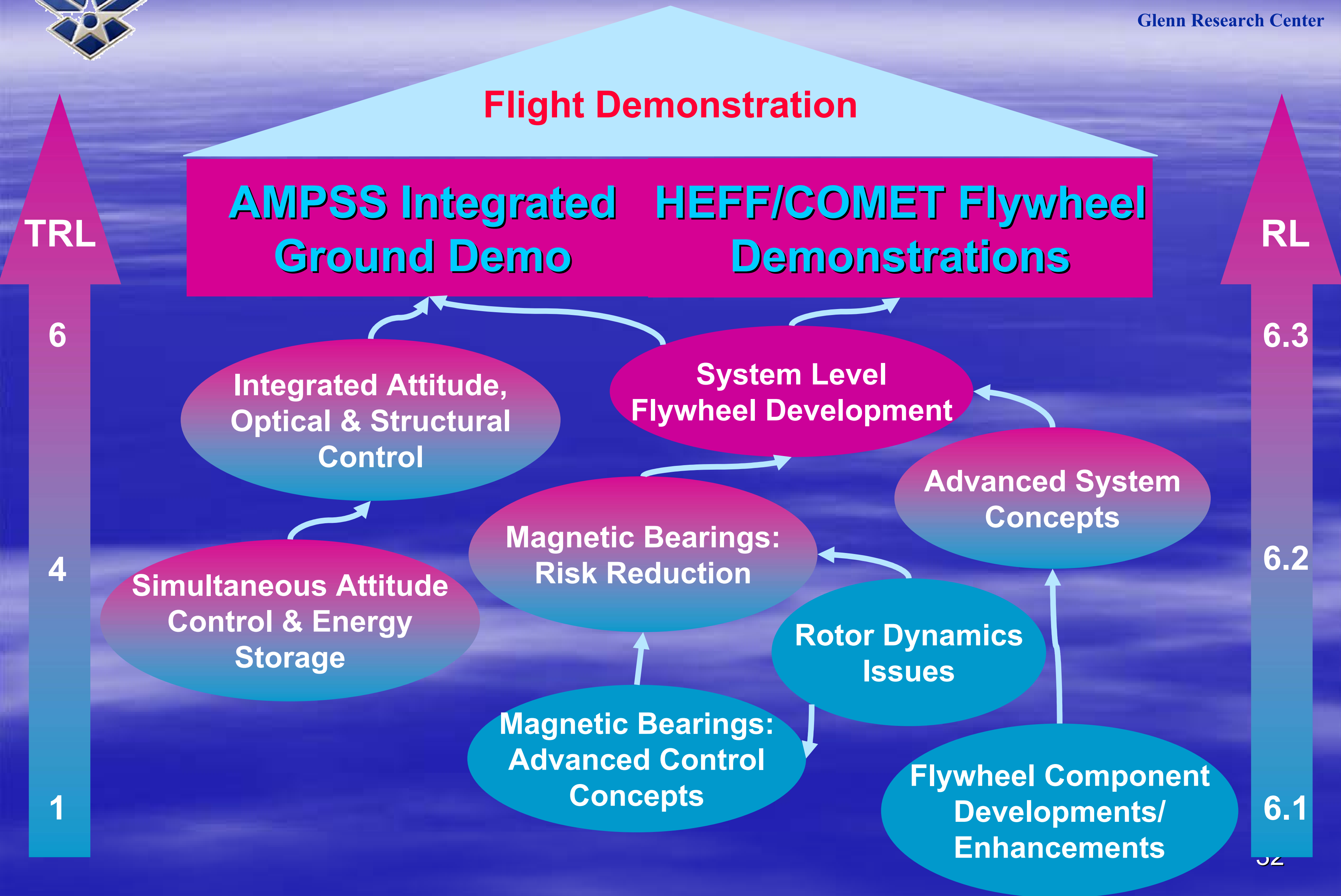
Flywheel Technology Development for Small Satellites
Develop high-speed motor & drive for open core flywheel system
(Penn State, NRA – NASA)



FACETS System Level Model Development
Develop simulation model to support analysis and HWIL testing
(CSA/Boeing SVS, In-house/Space Scholars – AFRL)

New Concepts in Low Cost, Higher Reliability and Less Complex Flywheel Systems
Basic research in passive bearings and inside-out flywheel configurations
(NASA)

What’s Next for Flywheels?


Flight Demonstration
AMPSS Integrated Ground Demo
HEFF/COMET Flywheel Demonstrations
TRL
6
4
1
RL
6.3
6.2
6.1
Integrated Attitude, Optical & Structural Control
System Level Flywheel Development
Advanced System Concepts
Magnetic Bearings: Risk Reduction
Simultaneous Attitude Control & Energy Storage
Rotor Dynamics Issues
Magnetic Bearings: Advanced Control Concepts
Flywheel Component Developments/ Enhancements

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What's Next for Flywheels?

- Technology Development
  - Conduct system level demonstrations of integrated power and attitude control capabilities for satellite applications
  - Demonstrate near term performance metrics at the system level by incorporating advanced technologies into higher fidelity hardware
- Program Development
  - Leverage technical successes with targeted high payoff applications as the road to flight

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Conclusions

- The Aerospace Flywheel Programs at AFRL and NASA have had significant successes in FY03
- A highly leveraged government, industry and academic capability exists to support a transition to flight
- FY04 looks promising with significant system level demonstrations and advanced technology developments to be completed
- AFRL and NASA continue to advocate and pursue near term flight opportunities

We are ready to fly!